Cold background, flight motion simulator mounted, infrared scene projectors developed for use in AMRDEC Hardware-in-the-Loop facilities

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ABSTRACT

This paper will present the results and progress of AMRDEC's development of two cold background, flight motion simulator (FMS) mountable, emitter array based infrared scene projectors for use in hardware-in-the-loop systems simulation. The goal for this development is the ability to simulate realistic low temperature backgrounds for windowed/domed seekers operating in tactical and exo-atmospheric simulations. Two projectors have been simultaneously developed; the first represents a streamlined pathfinder version consisting of a Honeywell emitter array and refractive optical system contained within an FMS-mountable environmental chamber cooled to -55 degrees Celsius. The second system is the full-capability version including a cryogenically operated BRITE II emitter array, zoom optics, integrated steerable point source and high-frequency jitter mirror contained within a similar FMS-mountable environmental chamber. This system provides a full-FOV cold background, two-dimensional dynamic IR scene projection, a high dynamic range independently steerable point source and combined optical path high frequency jitter control. Both projectors are designed to be compatible with operation on a 5 axis electric motor driven Carco flight motion simulator. Results presented will include design specifications, optical performance, sample imagery, apparent temperature and proposed future improvements.

Keywords: infrared, scene projection, simulation, hardware-in-the-loop, apparent temperature,

1.0 INTRODUCTION

1.1 AMRDEC HWIL facilities

The Aviation and Missile Research, Engineering, and Development Center (AMRDEC) under the command of the U.S. Army Research, Development and Engineering Command (RDECOM) on Redstone Arsenal, Huntsville, Alabama, has an extensive history of applying all types of modeling and simulation (M&S) to weapon system development and has been a particularly strong advocate of hardware-in-the-loop (HWIL) simulation and test for many years. The AMRDEC was previously under the command of the U.S. Army Aviation and Missile Command (AMCOM). The AMRDEC has been providing a full range of simulation support to Army Program Executive Officers (PEOs), Project Managers (PMs), other Armed Services agencies, and certain U.S. allies over the past 40 years. In addition, AMRDEC has M&S support relationships with the U.S. Army Space and Missile Defense Command (SMDC), and the Redstone Technical Test Center (RTTC).

Within the AMRDEC, the Advanced Simulation Center's (ASC) role is to provide a dedicated, government-owned, high fidelity, verified and validated simulation and test tool to assist the project office and prime contractor during missile system development, test, production, and fielding by providing value-added HWIL capabilities. The ASC consists of fourteen (14) HWIL facilities and focuses on the engineering-level simulations that pertain to the missile elements. The ASC is divided into three main areas: Imaging Infrared System Simulation (I^2RSS), Radio Frequency

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System Simulation (RFSS), and Multi-Spectral System Simulation (MSSS). The I^2RSS supports imaging and non-imaging infrared missile programs in both the near, mid and long wave infrared wavebands as well the visible waveband. The RFSS supports the X, K, Ka, and W band radio frequency missile. The MSSS supports the common aperture and/or simultaneous imaging infrared, visible, semi-active laser (SAL) and/or millimeter wave (Ka and W band) missile programs.

1.2 Cool background requirements in HWIL testing

AMRDEC's ASC currently tests many types of seeker missile systems, including imaging infrared systems. The ASC employs the use of state-of-the-art infrared scene projectors to support dynamic infrared scene simulations in testing of these missile systems. Typical infrared scene projector (IRSP) configurations present a dynamic range for any given thermal scene of 10ºC to 500ºC. Many infrared scenes however call for apparent temperatures that fall below the minimum apparent temperature achievable by these typical IRSP test configurations. Examples include winter or artic scenes for tactical missile systems, and space background for theatre missile systems. Non-windowed (exo-atmospheric) theatre based seekers require cryogenic backgrounds and are beyond the scope of this effort. However, windowed theatre seekers and tactical seekers have apparent minimum background temperature requirements within 10s of degrees of room temperature. Moderate reduction of the apparent background temperature can add significantly to the range of operational scenarios supported by the projector system. Previous approaches to attaining these moderate reductions in background have largely focused on 'table top' systems confined to large, fixed spaces. The most realistic simulations, however, are provided when coupling the UUT and the IRSP within a five-axis flight motion simulator (FMS). The challenges of integrating a cooled state-of-the-art infrared scene projector system within the limited constraints of the FMS are addressed within this paper for two systems: a prototype 'pathfinder' and the full capability IRSP.

2.0 GOALS AND IRSP MISSION

The overall goal of this development effort was the design, manufacture and testing of an FMS-mountable IRSP capable of achieving MWIR apparent temperature background levels in the range of 250-260 degrees K, a reduction of 25-35 degrees K from typically table-top, room-temperature IRSP systems. Secondary goals included the integration of auxiliary capabilities within the IRSP of continuous zoom, an independent high temperature point source, and high frequency LOS motion.

The IRSP was to be mounted on the forth axis of an all electric 5-axis flight motion simulator (FMS). The design of the FMS constricted the projector to a tight volume and weight budget. The volume restrictions required all aspects of the projector system to conform to a 32.5" x 17" x 19.5" box cantilevered off the forth axis. Figure 1 below shows the FMS IRSP frame configured at the given volume constraint limits. For comparison purposes, this volume is shown relative to the original IRSP analog drive electronics previously integrated onto other FMS systems. The drive electronics volume is represented in the second half of Figure 1 by the yellow volume.

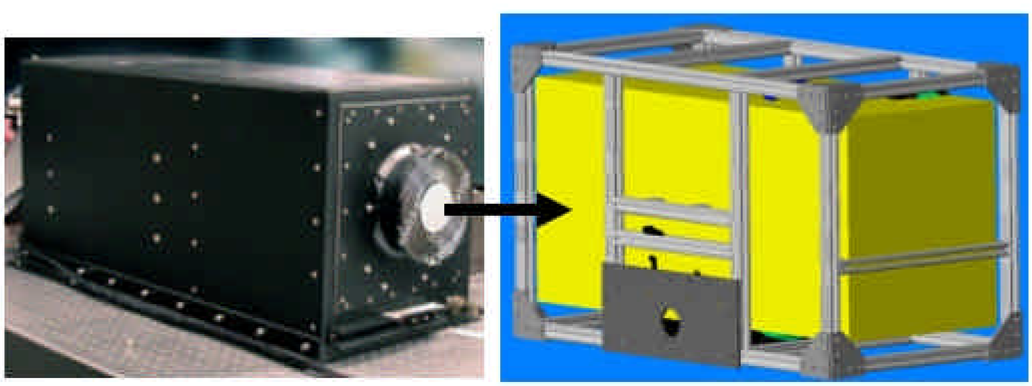

Figure 1 - IRSP volume compared to original IRSP analog electronics

The UUT LOS intercepts the IRSP volume near the center of the side facing the UUT, thereby further complicating the optical design. Due to the physical size of the source package and optical train, the optical path would have to be folded into a circuitous path within the enclosed volume. The advanced auxiliary features required the mechanical and optical consideration of dual object planes for a point source and dynamic emitter array, the zoom optics, a high-frequency jitter mirror, and a low-frequency steering mirror.

The weight constraint of the IRSP was not as rigid as the volume constraints. Unlike the repercussions of exceeding the volume constraints, excess weight of the IRSP would simply incur a penalty of reduced performance within the outer two axis of the five axis FMS. Based on the desired operating performance level of the FMS, an IRSP goal weight of 75 pounds was selected.

3.0 YUGO IRSP

3.1 System purpose

Early in the development process for this IRSP, it was recognized that the design and manufacture would take several months. It was determined that during this period a prototype system could be quickly assembled from in-house equipment that would provide valuable insight into several areas of concern. This limited-capability prototype system was nicknamed the 'YUGO' projector and incorporated many common elements of the FMS IRSP. These common areas included: compatibility with the FMS, the extruded aluminum support structure assembly, cooled emitter array and optics, cooled enclosure, and nitrogen purging. The primary goal of the YUGO was to gain experience and data in identified risk areas: mechanical structure, cooling techniques, purging, integration with off-table cooling, control systems, and overall performance.

A brief description of the YUGO IRSP is presented below. Figure 3 below shows a photograph of the integrated YUGO IRSP package. Minimum apparent background temperature data, along with other lessons learned from the YUGO assembly and testing, are provided in later sections.

Figure 2 - YUGO mounted on five axis FMS

Source

The YUGO IRSP incorporates a Honeywell cryo-vacuum compatible Multi-Spectral Scene Projector (MSSP) emitter array as the dynamic scene engine. The MSSP array was removed from its standard mount and repackaged onto a smaller custom mount incorporating a manual focus mechanism for optimization of the position while at cold temperatures. A smaller ion pump is used to maintain the array vacuum.

Optics

The optical system is an in-house narrow field of view, multi-element, refractive collimator optimized for operation over the full MWIR (3-5µm). The collimator's mechanical housing was modified to allow dry air purging into its inner cell to prevent condensation at low temperatures. The collimator was wrapped in copper tubing to conductively cool the lens housing by passing coolant through the tubing before it enters the emitter array cooling block. The IRSP collimating optics are designed to operate to a minimum temperature of -55ºC. The collimator is secured to the aluminum enclosure frame using a very low thermal conductance composite material.

Enclosure

The supporting frame structure was assembled from off-the-shelf modular extruded aluminum industrial erector set components. The structural pieces allowed for convenient modifications and design flexibility. With the limited capability requirements of the YUGO, the enclosure was reduced below the volume constraints to a size of 17" x 26" x

21”. This supporting frame is securely mounted to the FMS providing a rigid optical platform for the IRSP. Insulation is integrated into the support frame and capped with a twin wall polycarbonate panel. The interior of the IRSP is purged with dry nitrogen to prevent condensation at low temperatures.

Window

A vacuum insulated, double pane, optical window assembly seals to the enclosure to prevent condensation in the optical path and provide an optical port to interface the UUT. The window assembly consisted of two, 6-inch, anti-reflection coated calcium fluoride windows within a stainless steel housing creating a ½ inch vacuum gap.

Cooling System

Ultra-low temperature cooling is achieved using a recirculating chiller located away from the FMS. The chilled coolant is circulated through insulated hoses routed along an umbilical coolant line management system to the IRSP over a total of path length of sixty feet, round-trip. The coolant hoses are secured to the aluminum enclosure frame using a very low thermal conductance composite material. The ultra-low temperature chiller cools the collimating optics and resistor array cooling block through direct conduction by passing coolant through either a copper heat sink attached to the emitter array, or through copper tubing wrapped around the collimator housing. The chiller uses Syltherm XLT coolant with an operating range –80ºC to 250ºC. Thermocouples were attached to several locations within the YUGO to monitor the physical temperature of the components. These locations included the outside edge of the stainless steel window mount, the collimator body, and the emitter array cooling block.

Electronics

The Honeywell emitter array requires a set of support electronics which must be closely located to the array. These electronics provide the digital-to-analog conversion of the drive signals for operation of the array. For the YUGO, a miniature set of these ‘analog’ electronics, developed by the AMRDEC, are integrated within the enclosure. The interface cables to the digital drive electronics, located off the FMS, were threaded through the rotating fifth axis via an umbilical cable management system allowing for +/- 90 degrees of operation about the forth axis.

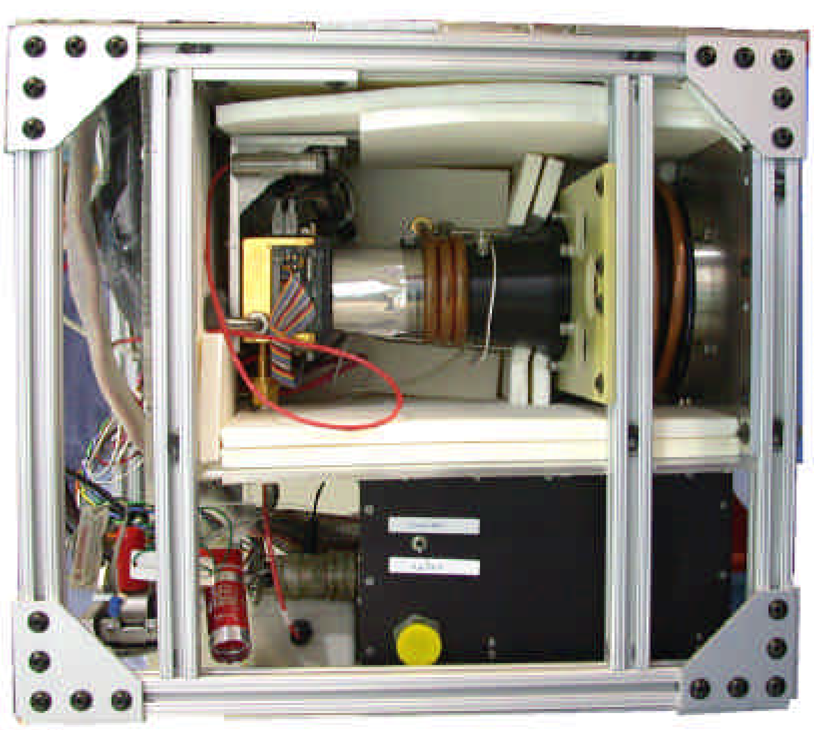

Figure 3 - Interior view of the YUGO IRSP

4.0 FMS IRSP

4.1 System Overview

This section describes the design of the full-capability FMS-mountable IRSP system. This description is broken down into the major sub-components of the FMS IRSP: the source package, projector optical assembly (POA), steering mirror, jitter mirror, enclosure, cooling system, and electronics.

Source Package

The FMS IRSP was specifically designed for compatibility with existing emitter array technologies. The system design allows for sufficient pupil relief and FOV coverage to incorporate either the Honeywell or Santa Barbara Infrared (SBIR) 512x512 emitter array packages. The FMS IRSP design also provides an additional object plane for simultaneous projection and operation of a quantum well laser diode source. Integrated with the steering mirror system, the laser diode provides a very high apparent temperature point source independent of the dynamic emitter array source[1].

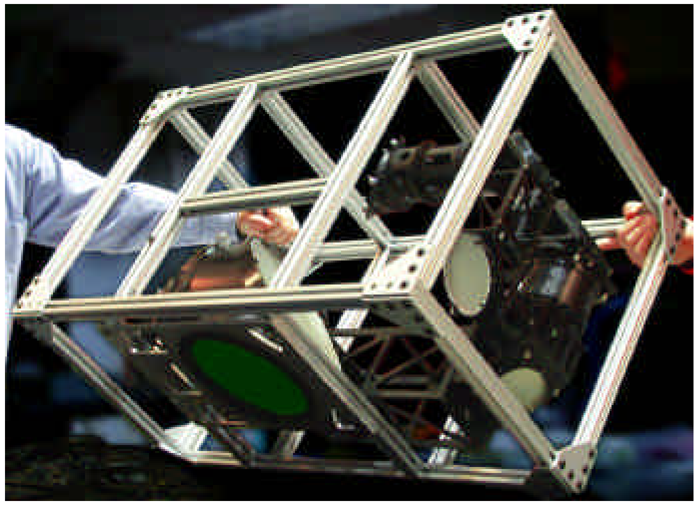

Figure 4. FMS IRSP

Projector Optical Assembly (POA)

The POA lies at the heart of the FMS IRSP and serves to integrate many of the other sub-systems into a single projector system. Figure 5 provides a mechanical solid model of the final POA design. The design and manufacture of the POA required over eighteen months to complete. Final design and manufacture was performed with the services of Janos Technology, Incorporated. The POA consists of three unique optical sub-assemblies referred to as the (1) zoom collimator, (2) the point source collimator, and (3) the afocal telescope.

The zoom collimator (ZC) provides the interface to the emitter array source and allows for various sized emitter packages to be coupled into a range of FOVs over a total zoom ratio of 2.2. The zoom collimator outputs an intermediate system pupil coincident with the jitter mirror.

The point source collimator (PSC) provides the interface to the laser diode point source and the fast steering mirror. The PSC design consists of a small, single-element collimator with the exit pupil located at the fast steering mirror, and an internal afocal relay. The fast steering mirror provides closed loop operation for apparent angular motion of the point source. The PSC outputs an intermediate system pupil coincident with the jitter mirror.

The afocal telescope (AT) provides the optical interface between the ZC and PSC output exit pupils and the UUT entrance pupil. The entrance pupil of the AT is coincident with the jitter mirror while the exit pupil lies 1018mm from the last optical element. This long relief provides the necessary standoff for operation of the POA on the FMS. The AT provides a 1.7X magnification resulting in a 76mm exit pupil at the UUT. The final section of the afocal telescope contains a ‘double-pane’ window assembly consisting of the last powered refractive element, a fold mirror, and the exit window. This area supports an isolated air-gap between the last refractive element and the exit window. This allows the interior of the FMS IRSP to be cooled while ensuring the interface to the external environment (the exit window) does not suffer from condensation.

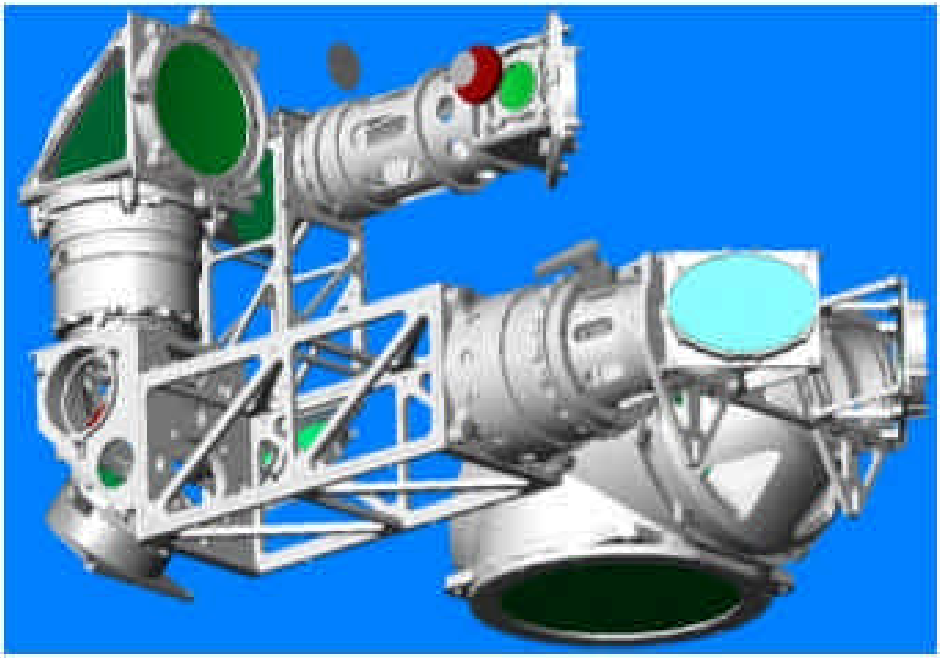

Figure 5: FMS IRSP POA elements

Steering Mirror

The fast steering mirror will use a commercial off-the-self product. The steering mirror has a maximum angular displacement +/-6 degrees mechanical, maximum angular velocity $\geq$6 Rad/sec mechanical and maximum angular acceleration $\geq$400 rad/sec mechanical. The control bandwidth is 400 Hz input and has a pointing accuracy of $\leq$50E-6 radians mechanical. The steering mirror is integrated into the point source collimator after the single lens laser diode collimator.

Jitter Mirror

The jitter mirror is located immediately following the location of the emitter array and laser diode beamcombiner and provides small amplitude, high frequency line of sight motion to the viewed image.

.Enclosure

The FMS IRSP enclosure consists of the same extruded aluminum structure material as that described in the YUGO IRSP section. The source package and POA mount to this aluminum frame at multiple attachment points. As with the YUGO, the interior of the FMS IRSP is insulated and purged with dry nitrogen to prevent condensation at low temperatures

Ultra-low temperature cooling

To date, the FMS IRSP has not undergone cold testing. However, all ultra-low temperature cooling will be identical to the cooling system described for the YUGO IRSP. The major exception is that the mechanism for cooling the optics will be convective, using a small radiator and fan assembly, rather than the conductive approach employed for the YUGO projector optics. The emitter array will continue to be cooled using coolant passed through the emitter array cooling block. All chilled coolant is circulated through the coolant and cable management system assembly to the IRSP by insulated hoses.

Electronics

The analog electronics for the IRSP incorporate the latest generation of miniaturized electronics for Honeywell emitter arrays. These electronics are being procured from Dynetics Corporation and are substantially smaller than the miniature package employed in the YUGO projector.

5.0 TEST AND EVALUATION

This section provides the sub-system and system test results collected to date for the YUGO and FMS IRSPs. To date, only the YUGO has undergone testing at cooled temperatures. Test data on the measurement of the apparent MWIR background temperature for this system is provided. For the FMS IRSP, test data is currently limited to optical performance and imagery testing only. Testing of the FMS IRSP at cooled temperatures will be reported on next year.

5.1 FMS IRSP optical performance

The optical specifications and measured performance values for the FMS IRSP POA are captured in Table 1. The optical system met or exceeded all design specifications measured to date.

Table 1: FMS IRSP optical system performance parameters

Parameter	Final Value
Volume	33”x20”x17.5”
POA Weight	42.6 lbs
Emitter Array Path FOV	±2 to ±3.4 degrees
Zoom Magnification	2.19
Point Source Path FOV	±2.8 degrees
Exit Pupil Size / Pupil Relief	76 mm / 1018 mm
Transmission	>70%
Encircled Energy	80% within 24um at short EFL 80% within 36um at long EFL

5.2 FMS IRSP sample imagery

Figure 6 below shows example imagery collected using a Honeywell emitter array and a commercial MWIR 512x512 camera.

Figure 6: FMS IRSP sample imagery

5.3 YUGO background apparent temperature

The experimental setup for measuring the apparent background temperature of the YUGO IRSP is shown in Figure 7. An infrared camera was used as the transfer mechanism between a blackbody and the YUGO projector. The camera was calibrated across the desired temperature span of -20 to 20ºC using a water-cooled plate blackbody. During calibration, the IR camera and blackbody were both enclosed in a glove box that was purged with dry nitrogen to allow the blackbody to operate at low temperatures without condensation.

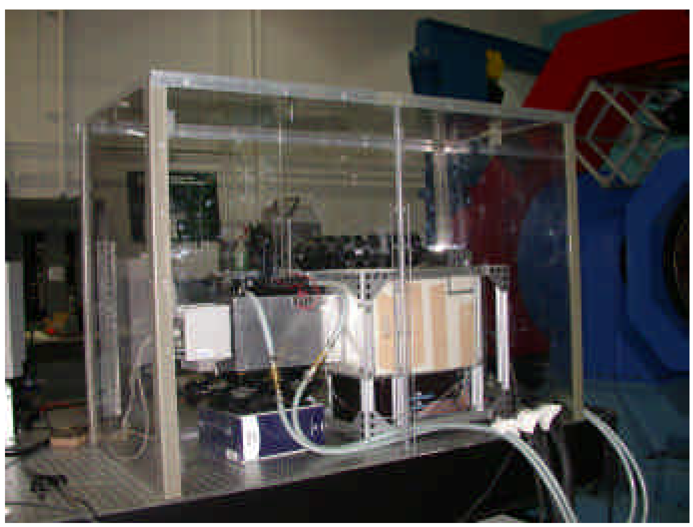

Figure 7. Experimental setup for apparent temperature measurements

After calibration, the blackbody was replaced by the YUGO projector and the IR camera was then used to image the YUGO IRSP output. The insulated YUGO emitter array and optics were cooled to several operating temperature points and camera data was collected at each point. The counts measured by the IR camera were converted to apparent temperature using the calibration data collected on the blackbody. Linear interpolation was used to determine apparent temperatures of the YUGO IRSP that fell between temperature data points of the blackbody. Figure 8 below plots the calibration curve generated from the data collected using the IR camera and blackbody overlaid with data of the cooled YUGO IRSP.

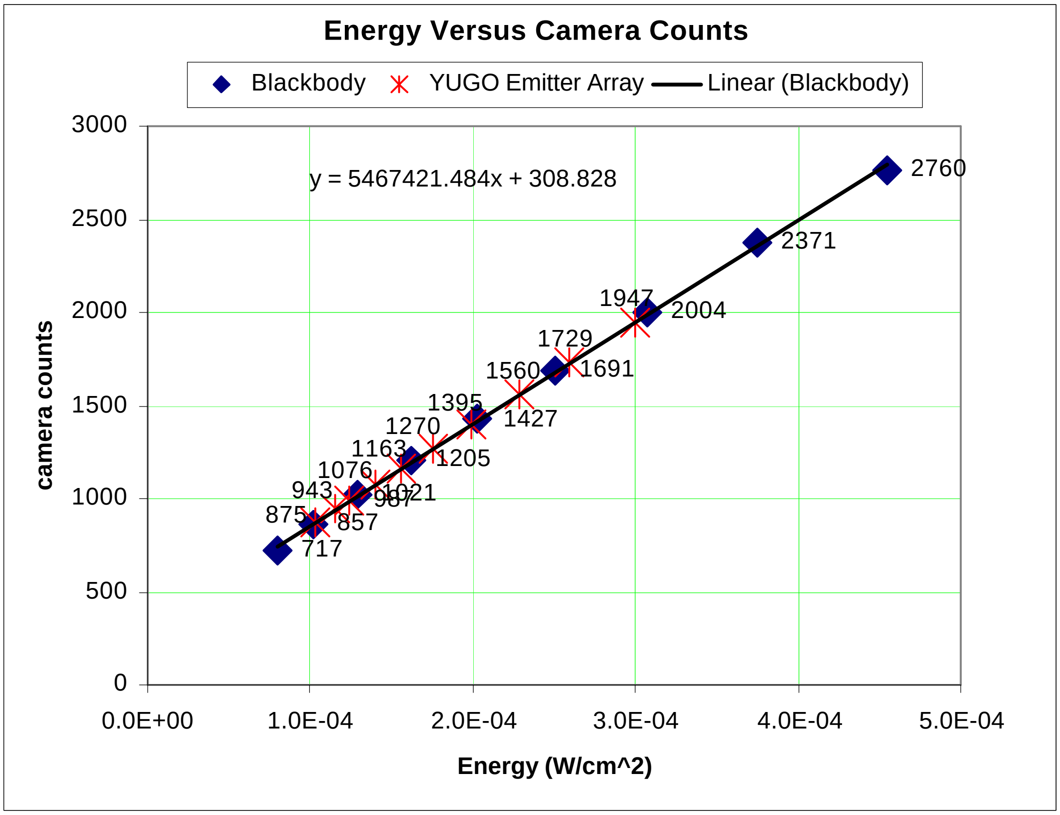

Figure 8: YUGO in-band energy overlaid with calibrated blackbody in-band energy.

The results for the YUGO minimum apparent background temperature are shown in Figure 9 for various emitter array cooling block temperatures. Not shown is the ultimate final temperature of the YUGO projector. Thus an emitter/optics operating temperature of 219 K resulted in an apparent temperature below 256 K, ~28 degrees below the apparent MWIR background temperature of other dynamic infrared scene projectors. All of these measurements were taken with the IR camera at room temperature (~23ºC).

The full capability FMS IRSP incorporates a larger number of optical elements to achieve the additional optical capabilities as compared to the YUGO projector. Due to the additional optics, the transmission of the FMS IRSP is expected to be lower than that of the YUGO. It is anticipated that this will lead to a moderately higher limit on the minimum attainable apparent background temperature. Modeling of the background contributors suggests the FMS IRSP minimum will be several degrees higher than that of the YUGO projector.

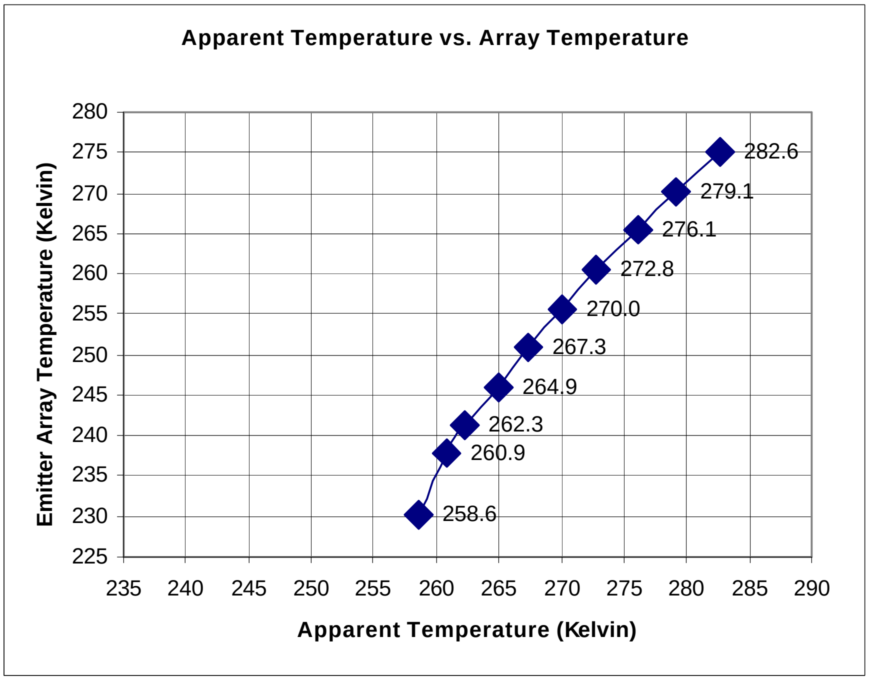

Figure 9: YUGO apparent background temperature as a function of array cooling block temperature.

6.0 LESSONS LEARNED

Several lessons were learned in the cold testing of the YUGO projector. To achieve an apparent background temperature below 260 Kelvin, the resistor array and collimator had to be cooled below –40ºC with the ultra low temperature chiller operating at –50ºC. At these low temperatures, elastomer compounds (i.e. nylon hose and o-rings) begin to stiffen considerably. Hoses lose their flexibility and o-rings lose their vacuum sealing properties. Some hose flexibility must be maintained on a flight motion simulator to allow for dynamic motion of the IRSP. A major hose rupture could be disastrous to much of the valuable projector hardware. Consideration of steel braided Teflon hose or even a thin wall flexible steel hose will be made for future operation of the YUGO and FMS IRSP.

Another issue with operation at such cold temperatures is maintaining array vacuum integrity when o-rings are approaching their operational low temperature limit. The first Honeywell resistor array cooled was packaged for room temperature operation. The vacuum integrity failed when the array cooling block temperature dropped below –30ºC. This array was then replaced with an array packaged for cryogenic operation. The major difference in this array's vacuum system was the removal of the conflat flange on the back of the array using a Viton gasket and replacing it with a Cajon VCR vacuum port on the bottom of the array using a metal gasket. This change eliminated one elastomer seal that was most likely to fail at low operational temperatures. To date, this array package has maintained vacuum at cooling block temperatures down to -55ºC.

The original hardware configuration did not provide any optical shielding between the collimator and emitter array. Exposure to the relatively warmer enclosure was suspected of adding to the apparent background through reflection off the emitter array. The addition of an internal cold baffle between the collimator and array dropped the apparent background temperature by 4 degrees. The baffle shielded the optical path from stray radiation entering the system from within the YUGO IRSP and absorbed radiation entering from off-axis outside the projector. The baffle connected to the optical collimator housing, through which it was conductively cooled, and extended to the array face.

All cooled hardware items must be secured to the aluminum enclosure frame. Attachment of the actively cooled hardware to the frame resulted in an undesirable cooling of the outer frame and condensation. Thermal isolation was

necessary to inhibit the formation of condensation on the outside of the enclosure. A composite material, G10, was selected for its excellent strength, low thermal conductivity, ease of fabrication, and availability. G10 mounts were fashioned for isolation of the collimator and coolant tubes entering the IRSP. G10 composite material is commonly used in cryogenic vacuum environments.

7.0 CONCLUSIONS

The AMRDEC ASC has demonstrated performance of a prototype FMS-mountable, cold background, two-dimensional, dynamic infrared projector system capable of achieving apparent background temperatures below -10ºC. A full capability projector, including additional source, positioning, and optical capabilities is currently under test. When complete, the FMS IRSP will provide the most advanced flight table compatible, cold background projector in operation.

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